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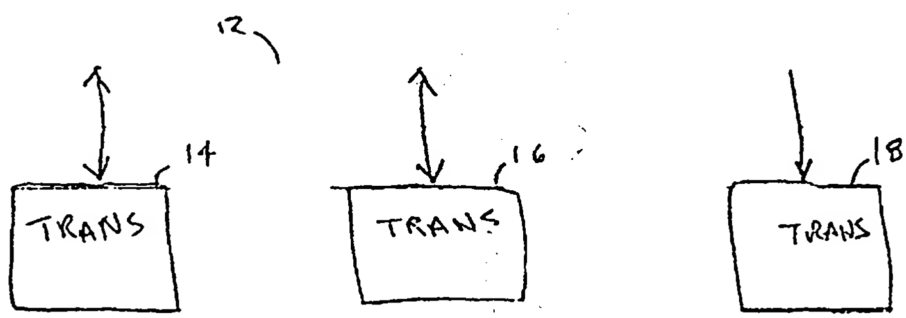

(57) Abstract

A method and apparatus are provided for distributing a plurality of information signals among a plurality of transceivers (14–18) through an optical communication system. The method includes the steps of introducing an optical splitter (20) into an optical waveguide (12) of the optical communication system and transceiving a refractively synchronized laser beam between the waveguide (12) and a local transceiver (22, 24). The refractively synchronized laser beam is modulated with an information signal of the plurality of information signals and a subcarrier. The subcarrier has a predetermined spectral and amplitude relationship with the information signal.

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OPTICALLY MODULATED LASER BEAM TRANSCEIVER SYSTEM

Field of the Invention

The field of the invention relates to lasers and in particular to optical modulation of lasers used for communication systems.

Background of the Invention

The use of lasers for the transmission of information in communication systems is generally known. Such use has typically been limited to amplitude or phase modulated systems that in use often attain a speed of several megabytes.

Methods have also been developed for multiplexing a number of channels of information onto a single laser beam using a process referred to as subcarrier multiplexing (SCM). For instance, one prior art reference frequency translates a number of information sources through the use of an equal number of microwave oscillators and combines the frequency translated signals in a microwave combiner. A continuous-wave laser may be used to produce a laser carrier that is modulated by the combined microwave signals in an external modulator of lithium niobate.

A set of Fabry-Perot (FFP) filters may be used to reecover a laser frequency of each information signal. Each FFP filter may be followed by a photodetector to detect the individual information signals.

While SCM is effective, it suffers from a number of operational problems. For example, such systems

often experience an unacceptable error rate and must rely upon error detection and correction.

In order to reduce errors, the prior art has taught that carrier and intermediate frequencies of SCM sources must be suppressed. Suppression of such signals is believed necessary to improve a signal-to-noise (S/N) ratio of any transmitted information side bands and for efficient channel usage.

Because of the importance of high speed communications, a need exists for more effective laser-based communication systems. Such systems should have an inherent noise immunity that is based upon the modulation techniques used at the transmission source instead of error correction and detection.

Summary

A method and apparatus are provided for distributing a plurality of information signals among a plurality of transceivers through an optical communication system. The method includes the steps of introducing an optical splitter into an optical waveguide of the optical communication system and transceiving a refractively synchronized laser beam between the waveguide and a local transceiver. The refractively synchronized laser beam is modulated with an information signal of the plurality of information signals and a subcarrier. The subcarrier has a predetermined spectral and amplitude relationship with the information signal.

Brief Description of the Drawings

FIG. 1 is a block diagram of a communication system under an illustrated embodiment of the invention;

FIG. 2 is a block diagram of a transceiver of FIG. 1;

FIG. 3 is a simplified signal flow diagram of the system of FIG. 1;

FIG. 4 is another simplified signal flow diagram of the communication system of FIG. 1;

FIG. 5 is an optical router & switch of the communication syst4em of FIG. 1;

FIG. 6 is a signal processing diagram of the communication system of FIG. 1;

FIG. 7 is a block diagram of the signal divider of FIG. 6;

FIG. 8 is a simplified signal flow diagram of the communication system of FIG. 1;

FIG. 9 is a simplified signal flow diagram of a bi-directional communication system of FIG. 1; and

FIG. 10 is another simplified signal flow diagram of a bi-directional communication system of FIG. 1.

Detailed Description of a Preferred Embodiment

FIG. 1 is a block diagram of an optical communication system 10, generally, in accordance with an illustrated embodiment of the invention. Under the embodiment, one or more transceivers 14, 16, 18 may be

interconnected via an optical waveguide 12 (e.g., a fiber optic cable) or via free space and may engage in the exchange of data and information with other transceivers 14, 16, 18 using the medium of the waveguide 12.

The transceivers 14, 16, 18 may be one-way or two-way devices capable of either transmitting and/or receiving information through the waveguide or fiber 12 or free space. For example, one transceiver 14 may be a cable channel receiver receiving blocks of television signals (e.g., 148 channels per block) for distribution to local subscribers. A second transceiver 16 may transmit the blocks to the first transceiver 14.

Alternatively, the transceivers 14, 16, 18 may engage in the simultaneous exchange of video, voice, data, or any combination of information formats over the waveguide 12 or fiber or free space. The information may be compressed or uncompressed. Further, any transceiver 14, 16, 18 may transceive information with any other transceiver 14, 16, 18.

FIG. 2 depicts an exemplary block diagram of a transceiver 14, 16, 18. As shown, each transceiver 14, 16, 18 may include a transmitter section 22 and receiver section 24. An optical splitter 20 may be provided as a means for interfacing with the waveguide 12.

The splitter 20 may be any optical splitting or coupling device capable of being placed in series with a waveguide 12 or fiber, without substantially interfering with transmission of optical signals traveling in either direction along an axis of transmission of the waveguide 12 (e.g., 90% of any

incident light passes through and 10% is diverted). The splitter 20 may function to divert a portion of any light propagating along the axis of transmission of the waveguide 12 into the transceiver 14, 16, 18, and visa versa. Under one preferred embodiment, a 90:10 optical beam splitter has been found to function advantageously. In general, a number of such devices are known in the art and, as a consequence, the details of the splitter 20 will not be discussed any further.

The transmitter 22 may be constructed as generally described and shown in copending U.S. Patent Application Serial Number 09/106,881, incorporated herein by reference. The receiver 24 may be constructed as generally described and shown in copending U.S. Patent Application Serial Number 09/106,881, also incorporated herein by reference.

FIG. 3 is a simplified block diagram of a portion of an optical communication system 10, where signal progression is shown occurring in a single direction (i.e., from left to right). A receiver 24 may receive many frequencies, but may select only a few (e.g, one) frequency for processing. FIG. 3 shows a structure by which a number of information signals may be distributed among a number of users, where the transmission of any one signal is substantially transparent to the transmission of any other signal.

Information is shown in FIG. 3 as being distributed to the user through a router & switch 42, 44. Unless clearly indicated otherwise, the router & switch 42 will be assumed to be a channel router (i.e., a switch) instead of a packet router.

Transmitter 30 may be a component of one or more upstream transceivers 14, 16, 18, transmitting signals for the benefit of users 48. The transmitted signals may each be a modulated block of TV signals S_m (e.g., 148 channels) that have been refraction multiplexed onto a subchannel of a transmitted signal using refractive synchronization technology (RST) and sampled, or upshifted, at a sampling clock frequency Cf_n, as shown schematically in FIG. 4. Modulation and/or upshifting may be accomplished within a electro-optical differential multiplexer (e.g., an External Modulator by UTP SITU APE, Marconi LC 1000, etc.).

Optical refractive synchronization is a process whereby a controlling clock subcarrier and information signal are used to modulate an optical signal. Fundamentally, the process of refraction is the change of energy, direction or speed of a light beam which is propagating through a medium. In a first case, the change in direction may be a continuous bending of the light beam and of the subsequent change of the speed of light in the medium which is referred to as the index of refraction of the material. In a second case, there is an abrupt change in the index, polarity, or phase of the medium which directs the energy out of the medium, or changes the ability of light to pass through the medium, thereby absorbing the energy. This second case is the technique employed in optical refractive synchronization. The light is passed through a crystal which has the refractive index changed abruptly, by imposition of an electric field, by passing a controlling signal through the crystal, which then causes the crystal to allow the light to pass through,

or be absorbed in the crystal at the frequency of the controlling signal. This optical modulation is performed, therefore, through control of the refraction and polarization signal of the optical crystal.

By combining the frequencies of various sources and optically modulating them onto a respective clock frequency with an appropriate (i.e., predetermined) sampling frequency and amplitude ratio, it is possible to synchronize all of the information signals to their respective optical light beams. It then also be comes possible to combine them with other light beams with similar optical modulation at singularly different clock frequencies and to nest these optically modulated beams onto yet another yet higher clock frequency by using optical refractive synchronization.

Although refractive synchronization technology (RST); as outlined herein, is superficially similar to the well-known concept of subcarrier multiplexing commonly used in the microwave transmission arena, it differs from traditional microwave subcarrier multiplexing in a number of aspects. First, the prior art accomplishes subcarrier multplexing under an rf format. More specifically, the prior art has not provided a mechanism through which optical signals could be multiplexed directly and coherently. Without a mechanism for coherently mixing optical signals, subcarrier multiplexing could not be extended to optical communications systems, without the step of first mixing the information signals under an rf format and then transmitting the previously mixed signals under an optical format.

Further, refractive synchronization of optical signals involves substantially different processes than microwave subcarrier multiplexing. For example, RST is a significant advancement whose efficacy is dependent upon two fundamental relationships:

The first, relates the substantially exacting choice of the clock (subcarrier) amplitude with respect to the amplitude of the maximum spectral amplitude present in the information signal spectrum. [Note: In the conventional subcarrier multiplexing literature there were only heuristic rules like make the subcarrier amplitude at least 10 dB more than the signal spectrum maximum amplitude as opposed to the exacting mathematical analysis shown in Dr. Palmer's work.

The second, relates the substantially exact required frequency of the clock (subcarrier) to the amplitude ratio determined by the first relationship. this frequency can be adjusted to account for baseband noise present in the information signal. [Note: this function is completely described in the paper (attached as Appendix I) by J. R. Palmer, Frequency Sampling Ratio as a Function of the Ratio of Amplitudes Between the Clock Frequency and the Modulated Frequency for Verisimilitude-Homodyne Laser Transmitter-Receiver.]

In summary, the use of RST implies the *adherence to well-defined mathematical schemes to determine the amplitude ratios employed in the clock (subcarrier) and well-defined mathematical determination of the required frequency of the clock* (subcarrier) as a function of the previously determined amplitude ratios and/or possible baseband noise in the system.

Once the signal from the laser 166 is modulated with the information signal by refractive synchronization, the signal may be upshifted within a second electro-optical differential multiplexer 170 (e.g., an External Modulator by UTP SITU APE, Marconi LC 1000, etc.). Upshifting may be accomplished at any clock frequency with an appropriate sampling rate as determined from the Palmer Sampling Modulation Transfer Function equation as follows:

$$f^{-1}_{0sample} = \frac{2}{\pi}\left(\cos^{-1}\left(\frac{A}{Ao}\right) - \left(\frac{A}{Ao}\sqrt{1.0 - \left(\frac{A}{Ao}\right)^2}\right)\right)$$

where A is the modulated signal amplitude, Ao is a clock frequency amplitude.

For the case where a noise signal is included as part of the baseband signal, the equation can be modified as follows:

$$f^{-1}_{0sample} = \frac{2}{\pi}\left(\cos^{-1}\left(\frac{A}{Ao}\right) - \frac{A}{Ao}\sqrt{1.0 - \left(\frac{A}{Ao}\right)^2}\right)\left(\left(\frac{2J_1(M)}{M}\right)\left(1.0 - \frac{A}{Ao}\right)\right)$$

where M is $8\pi\delta A/A_o$ and δ is baseband noise amplitude/$2A_o$ and $J_1(M)$ is a Bessel Function of the First Kind of Order 1. Further, a required minimum clock sampling frequency for $A_0 = (1/f_{0sample})f_{max}$ where f_{max} is the highest frequency represented in the modulated signal A. From a practical point of view the best results have been found to occur where $A/A_o<1.0$ (i.e., the clock

amplitude A_o is 2.0 to 7.0 times larger than the modulated signal amplitude A).

As shown in FIG. 4, each block of signals S_m may be modulated onto a laser beam either by modulation of a junction current of a source DFB laser or by external refraction synchronization. The signals S_m may be provided under any number of formats (e.g., a first block of signals S_1 may be 148 TV channels under a FDM format, a second block of signal S_2 may be a T1 telecommunications trunk signal, a third signal S_3 may be provided under the SONET format used in a wide area network (WAN), etc).

The modulated laser beam may then be sampled or upshifted using a subcarrier sampling clock Cf_n having a magnitude 2 to 7 times larger than the maximum value of the modulation information spectrum of an underlying block of the blocks of signals. Sampling, or upshifting, of the blocks of information may be used to form each of the modulated blocks of information signals superimposed on a laser beam which may be, in turn, propagated among transceivers 14, 16, 18 using the appropriate medium.

Page 7 of Appendix I is a graph which relates sampling frequency, amplitude ratio and noise levels. The ordinate of the graph is the inverse of the sampling frequency. The abscissa is the signal/clock amplitude ratio.

To use the graph of page 7 of Appendix I, a user may enter the graph using a sampling frequency and amplitude ratio to recover a noise level that may be experienced by a particular system design. Alternatively, a user may select a maximum acceptable

noise level and sampling frequency and enter the graph with the noise level and sampling frequency to recover an amplitude ratio necessary to limit noise to that noise level.

FIG. 11 depicts laser frequencies of modulated blocks of information signals 302, 306, 310, 318 that have been superimposed onto the laser beam which propagates among transceivers 14, 16, 18 along the waveguide 12. Also shown with each information block (e.g., 302) is a corresponding sampling clock Cf_n (e.g., 304), lying between the information blocks.

Sampling the modulated laser beam at non-coincidental clock frequencies Cf_n, may be used to move each modulated signal block to a non-interfering (i.e., non-overlapping) subchannel spectral location with regard to every other subchannel through use of predetermined set of sampling or upshifting frequencies Cf_n (e.g., Cf_1=2.5 GHz, Cf_2=3.6 GHz, Cf_3=4.7 GHz, etc.). Each source of data S_m may be assigned one of the subchannel clock (subcarrier) frequencies Cf_n. For example a first signal S_1 may be assigned a first clock Cf_1. A second signal S_2 may be assigned a second clock Cf_2, and so on.

The subchannels may then be optically combined, detected and modulated onto another laser beam to nest a block of subchannels. The detected block of subchannels may be modulated onto the other laser beam using external (diode junction) modulation or RST. The modulated block of subchannels may then be sampled at (upshifted to) a higher system sampling clock frequency Cf_x (e.g., 100 GHz, 200 GHz, etc.) using optical

refractive synchronization to form a nested modulated block of subchannels superimposed on a laser beam, where each subchannel is defined by the information block and its associated subcarrier (clock).

Further, a first nested block of subchannels sampled at a first system clock frequency Cf_x may be combined with a second nested block of subchannels at a second system clock frequency Cf_{x+1} in a splitter 20 of a downstream transceiver 34 (FIG. 3). Such combined blocks of subchannels (depicted by arrows 38 in FIG. 3) may propagate through the waveguide 12 and be decoded in downstream receivers (e.g., receiver 36).

Within any particular transceiver 14, 16, 18 of the system 10 (e.g., receiver 24 of transceiver 34 of FIG. 4) the nested block of subchannels may be recovered by downshifted using a mixer in the receiver 24 with the system clock Cf_x for a predetermined block of subchannels, which are then returned to baseband. Similarly, a block of signals may be recovered for each subchannel of a block of subchannels by downshifting using a mixer in the receiver 24 with the subchannel clock Cf_n. Synchronization to the system subcarrier or subchannel clock may be accomplished within the receiver through the use of a phase-locked-loop (PLL), operating at the subcarrier frequency, and a downshifting mixer.

FIG. 5 depicts an optical channel routing structure 50 that may be disposed between the splitter 20 and a detector 80, 82 of the receiver 24 for routing subchannels of a block of subchannels. The routing structure 50 provides switching fabric for routing the

subchannels to selected channel decoders within the receivers 24.

Depicted within the channel routing structure 50 are two optical routing channels 100 102. The routing channels 100, 102 may be constructed using 8x8 photonic switches (e.g., UTP Model YB-150-180) 74, 76 or 16x16 photonic switches 70, 72. The use of 16x16 switches 70, 72 may be used to reduce the size of the switching structure where size is at a premium, or where the number of decoded channels is large. Where size is less critical, 8x8 switching devices 74, 76 may be used.

Included within the routing structure 50 are optical inline amplifiers 52, 54, 56, 66, 68 which function to increase the amplitude of the received optical signal. The inline amplifiers may be any appropriate erbium doped fiber amplifier (EDFA) device.

Inline 50:50 beam splitters 60, 62 may be provided where two or more optical routing channels 100, 102 are provided. Mirrors 58, 64 may also be provided, where necessary to direct the optical signals to appropriate switching elements 70, 74.

Decoding of a block of signals may be accomplished by detecting a subchannel signal or nested block of subchannels in a corresponding photonic detector (photo sensor) 80, 82. The detected signals may then be frequency translated to a baseband frequency by first homodyning it with predetermined system clock frequency Cf_x and/or a subchannel clock Cf_n assigned to the channel.

FIG. 6 shows a block diagram of an optical decoder. As shown, a photonic detector (e.g., a

photodetector) 80, 82 may be followed by a signal divider (block selector) 84 and signal amplifier 86. The detector subsystem (FIG. 6) receives the optical signal from the optical router & switch (FIG. 5), converts the optical signal into an electrical signal for further processing by the receiver block selectors, separates the signal into the required multiple output signals, amplifies the separated signal and sends it to the corresponding receiver block selectors.

FIG. 7 is an exemplary block diagram of a block selector of the signal divider 84 of FIG. 6. One or more block selectors of the signal divider 84 may be used to recover signals S_m from modulated blocks of signals or to recover modulated blocks of signals from a nested modulated block of subchannels. A block selector of the signal divider 84 may be provided for each nested block of subchannels and for each signal (e.g., S_1, S_2 . . . S_m) of a block of signals to be decoded. Different sampling frequencies may be assigned to each block selector.

To ensure that the sampling clock frequencies of the transmitter and receiver are locked to one another, a homodyning circuit (FIG. 7) is provided. The first input filter 102 is a low-pass filter set to extract one of the sampling frequencies carried on the laser beam. Specifically, this filter 102 eliminates signals in the frequency range corresponding to the upper sideband in the sampling receiver subsystem. The input signal is then split in the first splitter 104. The outputs are fed into the first mixer 108 and the second mixer 110. These signals contain the lower sideband and transmitted sampling clock frequency.

A sampling frequency generator 116 may be provided in each receiver block selector. This sampling frequency generator 116 is intentionally offset in its operating frequency from the sampling frequency generator in the respective transmitter. This offset frequency varies between 200 and 500 MHz (e.g., by 200, 300, 400 or 500 MHz). The offset allows for the homodyning of the two signal sources (transmitter and receiver) and provides for an accurate regeneration of the transmitted sampling frequency. The purpose of the homodyning circuit is to compensate for any drift in the transmitted sampling frequency.

The output of the sampling frequency generator 116 is fed into the second splitter 118. The output of this splitter 118 feeds the second mixer 110 and the third mixer 120. The output from the second mixer 110 is the difference between the original transmitted sampling frequency and the receiver's sampling frequency. The difference is approximately 200, 300, 400 or 500 MHz. The difference may be the exact offset frequency between the transmitter and receiver's sampling frequencies, provided the transmitted sampling frequency has not drifted up or down in frequency.

The output of the second mixer 110 is fed through the third filter 112 to the other input to the third mixer 120. The third filter 112 is a narrow bandpass filter set to eliminate all signals except the difference between the two sampling clock frequencies (i.e., transmitter and receiver).

The output of the third mixer 120 is an exact replication of the received transmitted (i.e., the transmitter) sampling frequency. The output of the

third mixer 120 is filtered in the second filter 114 and fed into the other input port of the first mixer 108. The second filter 114 is also a narrow bandpass filter set to eliminate all frequencies except the required sampling frequency used to demodulate the received data block.

The inputs to the first mixer 108 consist of the original received data block with its corresponding sampling frequency and the regenerated sampling frequency from the receiver block selector. Here the received transmitted sampling frequency and the receiver's sampling frequency cancel one another and all that is left is the required signal data (e.g., S_1, S_2, S_3 . . . or S_m) or modulated blocks of signals. This data is sent from the output port of the first mixer 108 to the output driver 106 for further signal processing. If the required output of the receiver block selector is RF, then the signal is sent directly to an output connector. If the required output is to be converted into another optical signal, then the signal is sent to a laser driver and converted back into its original optical format.

Amplifiers 86 are provided in the homodyning circuit as needed to keep the signals at the required levels for further processing. These amplifiers 86 may be either of a variable gain variety or of a fixed gain type.

Once a nested optical block of subchannels has been decoded, the individual radio frequency signals (i.e., S_1, S_2 . . . Sm) may be routed from an output of a receiver 24 (FIG. 3) through use of a router & switch 42 and associated controller 46 to a user 48. Control

of the router & switch 42 may be accomplished from external sources, or, from the decoded signal itself.

For example, where a signal (e.g., S_1) is a telecommunications trunk line (e.g., a T1 line), a repeating data structure of interspersed data and control frames may be provided (e.g., 28 data channels, 2 control channels). The control channels may be used to provide assignment and routing information for each of the other 28 channels. Further, it would be clear to a person of skill in the art that the T1 channel is bidirectional, allowing the flow of control or data in either direction over the T1 link.

Alternatively, where a channel S_m is structured for support of a WAN, packet switching may be used for the transmission control. Where packet switching is used each packet may contain a packet header including identifying information identifying a target of each packet.

Such control information received from the user 48 (for information to be transmitted over the system 10) as channel associated signaling or intercepted by the router & switch 42 (for information received from the receiver 24) and forwarded to the controller 46. The controller 46, in turn, may use such information in conjunction with a look-up table to identify a pair of switch ports of the router & switch 42 for successfully routing of the information to the desired destination.

Turning now to the system 10, as a whole, a series of examples will be offered as a means of understanding the operation of the system 10. In a first example (FIG. 8), it will be assumed that optical signals flow in only a single direction (i.e., left to right).

Further, it will be assumed that at least some channels S_m may be dedicated to specific purposes.

For example, channel S_1 of information channels S_m may be dedicated for the transmission of information from transceiver 14 to transceiver 16 of FIG. 1 using subchannel sampling frequency Cf_1. Similarly, channel S_2 may be dedicated for the transmission of information from transceiver 16 to transceiver 18 using subchannel sampling frequency Cf_2. Channels S_3 and S_4 may be dedicated for transmitting information from transceiver 14 to transceiver 18 using sampling frequencies Cf_3 and Cf_4. A system sampling frequency of Cf_X may be used as a nesting sampling frequency.

Under these conditions, the nested block of information received by the second transceiver 16 (FIG. 8) would include signals S_1, S_3 and S_4. The nested block of subchannels may be recovered using the homodyning circuit (FIG. 7) and the system sampling frequency Cf_X. The transceiver 16 may recover the first signal block S_1 using its assigned subchannel sampling frequency Cf_1. The signal S_1 may be forwarded to its assigned destination through an associated router & switch 42.

The transceiver 16 may also function to forward signals S_3 and S_4. The transceiver may sample S_2 at its sampling frequency Cf_2 and optically combine it with S_3 and S_4. The nested block of S_2, S_3 and S_4 may be sampled at a new system frequency of Cf_{X+1} and forwarded through the splitter of the transceiver 16 to transceiver 18.

As an alternative, nesting is not necessary and may not be used for implementation of the above example. A first laser may be modulated with the first information block S_1 and sampled at the first blocks sampling frequency Cf_1 to provide a first modulated laser beam. A second and third laser may similarly be used for transmission of the third and fourth information signals S_3, S_4. The first, second and third modulated laser beams may be optically combined and transmitted to the second transceiver 16. The second transceiver 16 may recover the first information signal S_1 and transmit the second information signal S_2, in its place to the third transceiver 18.

After leaving the transceiver 16, the beam contains the original set of sampled and modulated signals S_3 and S_4, plus the newly sampled and modulated signal S_2. This new set of signals can be accessed anywhere on the network 10 using a standard transceiver 14, 16, 18 which has been designed to demodulate the clock frequencies Cf_n and provide any of the signals that were added subsequent to the initial transmission. As discussed, the system of FIG. 8 is a linear system, transmitting in one direction.

For bi-directional networking, schematically represented in FIG. 9, the concepts discussed above still apply. To make the linear network of FIG. 8 be-directional, the choice of clock frequencies is an important aspect of system performance. The basic components of the bi-directional transceivers 200, 204, 206 of FIG. 9 may be found in the transceivers 14, 16, 18 of FIG. 1. For example, the transceiver 200 may

include two transmitters 22. Other transceivers (e.g, 206) may contain one or more receivers 24. Signal from routers 204, 206 may be modulated using RST and combined in a Cassegrain optical combiner 202.

In the network of FIG. 9, the transceiver 200 may be configured with two ports for receiving information. One port may be connected to a router & switch 208 which can add data which is shown as being transmitted westbound and another port may be connected with a router & switch 210 which supply data which may be transmitted eastbound. The transceiver 206 in the bi-directional system can receive data that is traveling either east or west and provide that data to routers 212.

Where full bi-directional operation is required each transceiver 214 (FIG. 10) may be provided with two transmitters 22 and two receivers 24. Two optical routers 50 may also be provided for routing purposes.

With the transceiver 214 of FIG. 10, data may be transmitted in both directions without mutual interference even using the same clock. The same laser frequency may also be used where there is a phase offset among the lasers. Further, the transceivers 214 may also using bi-directional time division multiplexing as a means of further sharing channel capacity.

As a further method of operation of the system 10, the transceivers 14, 16, 18, 200, 214 may be operated under an ethernet format. Ethernet-like operation is achieved by having a bi-directional system 10 with a laser at each end of the fiber 12 to create the "ether" for signal transmission. This actually creates

muitiple "ethers", one for each allowable frequency band. There are two distinctly different implementations possible, a fully asynchronous method and a simple master-clock method. In the master-clock method, one or both ends nodes (e.g., transceivers 14, 18) transmit the various reference frequencies continuously, and all the other nodes (e.g., transceiver 16) acquire and use these frequencies. The advantage of having only one of the end nodes transmit the reference frequencies is that it greatly simplifies the construction of the intermediate nodes because the clock frequency is the same for both directions of data transmission. When a node has data to be transmitted, it first determines if there is any incoming data present in the ether. If the ether is clear, the node proceeds to transmit the data but still monitors the incoming data paths for data from another node. If a collision occurs, the node waits a random interval and tries again. Note that each node never sees its own data transmitted in the ether - all other nodes are "downstream" in the relevant direction of data transmission, so collisions are detected by data being received at the same time that data is being transmitted (plus a small guard-time dictated by the size of the system).

In the fully asynchronous method, each node transmits its own reference frequency whenever it has data to send. The node first determines if there is a similar reference frequency being received from another node. If not, the node sends out its own reference frequency. After a preset interval, during which the destination node acquires the reference frequency, the

transmitting node proceeds to send the data, but still monitors the incoming data paths for a similar reference frequency from another node. After the data has been sent, the node also stops transmitting its local reference frequency. If a collision occurs, the node waits a random interval and then tries again. Note that as in the master clock method, each node never sees its own reference frequency transmitted in the ether, so collisions are detected by a similar reference frequency being received at the same time that the local reference frequency is being transmitted.

The system 10 may also operate under a token ring format. To achieve a true token-ring like system, each node must be able to remove data from the laser beam (instead of just extracting it), thereby restoring the original unmodulated beam. This can only be done in the optical domain, for example by pinholing the laser beam to strip off the modulation sidebands. After the beam has been stripped, the data may be examined for destination and used locally, if so intended. Any data needing to be passed through the node then may be remodulated back onto the outgoing laser beam. In practice, this is achieved by receiving the complete spectrum into the RF domain from the incoming beam, filtering out the frequency bands to be removed, and then transmitting the remaining spectrum along with any new data to be transmitted. One node in the ring is the "master" which generates both the raw laser beam and the reference frequencies. Each node in the ring looks at the received data stream to detect the "token" being passed around the ring.

Until the token is received each node that wishes to transmit just passes through everything it receives, that is not addressed to it. If the node has no data to send, it transmits the received token to the next node in the ring. Otherwise, it transmits the data waiting to be sent and then transmits the token. During data transmission, any data received in the appropriate frequency band is removed. Note that each frequency band is a separate ring within the fiber.

If stripping the data results in too much attenuation of the laser beam, it may be necessary to use optical amplifiers at strategic points around the ring, or even to regenerate the beam using multiple lasers distributed round the ring. In the extreme case, the network degenerates into a circular sequence of point-to-point links, each with its own laser. An alternative approach is to use an unmodulated beam in the reverse direction and splitting it at each node to use part of it to boost the power of the stripped beam; this technique could be extended to eliminate stripping altogether.

A variant token-ring like system can be achieved by double-frequency allocation. Each "ring" within the fiber is assigned two reference frequencies. The first reference frequency is used for passing the token around the ring and for sending data from an originating node around to the master node.

The second reference frequency is used for sending the data from the master node (no matter where it originated) around the whole ring. This removes the necessity for nodes to strip data from the laser beam. Effectively, the network is similar to an orbital

satellite system with one frequency used for the uplink and a different frequency used for the downlink. Since the "token" transmitted is now send by all downstream nodes, the transmitter must encode its own identifier into the taken, and each node has to know which other node is immediately upstream so that it can discard inappropriate tokens.

An alternative variation is to utilize the direction of transmission around the ring instead of using two reference frequencies. One direction may be used for transmission to the master node, and the other direction is used for distribution out from the master node. With this two-directional method of operation, the functions of the "master" node can be split between two separate sites provided the tail-end master can transmit the token back to the head-end master on the reverse channel. The "ring" is then from the head-end node to the tail-end node in one direction and then from the tail-end node back to the head-end node in the other direction. Note that this is still substantially different from a circular ethernet by virtue of the token-passing mechanism versus the asynchronous collision-detecting mechanism, and also by the data reception being limited to only one direction of data transmission.

In another embodiment, a multi-drop system 10 can be achieved in a manner similar to token-ring like system described above. In this variation, the token-passing control mechanism is replaced by a poll/response system. The master node sends out a "poll" token to each node in turn and gets back either a data block or a no-data token. The data block itself

can be a request for channel bandwidth, and then the system transforms into a CDMA-like system. Forcing the data blocks and poll/response tokens to be fixed-size entities allows the network to be transformed into a TDMA-like system. For a network 10 with a small number of nodes, each node may be allocated its own reference frequency, and then the network transforms into an FDMA-like system. Combinations of these various methods can also be implemented to suit specific network requirements. In particular, a single master node can have multiple fiber links attached, resulting in a star-like network (or even a concentrator).

A specific embodiment of a method and apparatus of distributing a plurality of information signals among a plurality of transceivers through an optical communications system according to the present invention has been described for the purpose of illustrating the manner in which the invention is made and used. It should be understood that the implementation of other variations and modifications of the invention and its various aspects will be apparent to one skilled in the art, and that the invention is not limited by the specific embodiments described. Therefore, it is contemplated to cover the present invention any and all modifications, variations, or equivalents that fall within the true spirit and scope of the basic underlying principles disclosed and claimed herein.

Claims

1. A method for distributing a plurality of information signals among a plurality of transceivers through an optical communication system, such method comprising the steps of:

introducing an optical splitter into an optical waveguide of the optical communication system; and

transceiving a refractively synchronized laser beam between the waveguide and a local transceiver, said refractively synchronized laser beam modulated with an information signal of the plurality of information signals and a subcarrier, said subcarrier having a predetermined spectral and amplitude relationship with the information signal.

2. The method for distributing a plurality of information signals as in claim 1 wherein the predetermined spectral and amplitude relationship further comprises solving an equation as follows:

$$f_{osample} = \frac{2}{\pi}\{\cos^{-1}(\frac{A}{A_o}) - \{(\frac{A}{A_o})\sqrt{[1.0 - \left(\frac{A}{A_0}\right)^2]}\}\},$$

where A is modulated amplitude frequency and A_O is clock frequency amplitude.

3. The method for distributing a plurality of information signals as in claim 1 wherein the predetermined spectral and amplitude relationship further comprises solving an equation as follows:

$$f_{osample} = \frac{2}{\pi}\{\cos^{-1}(\frac{A}{A_o}) - \{(\frac{A}{A_o})\sqrt{[1.0 - \left(\frac{A}{A_0}\right)^2]]\}\}\{\frac{2J_1(M)}{M}\{1.0 - \left(\frac{A}{A_0}\right)\}\},$$

where A is modulated amplitude frequency, A_0 is clock frequency amplitude, $M = \frac{8\pi\zeta A}{A_0}$, and ζ equals baseband noise amplitude divided by $2A_0$.

4. The method for distributing a plurality of information signals as in claim 1 wherein the step of transceiving the refractively synchronized laser beam further comprises transmitting the refractively synchronized laser beam from the local transceiver, through the waveguide, to another receiver.

5. The method for distributing a plurality of information signals as in claim 4 wherein the step of transmitting the refractively synchronized laser beam further comprises refractively synchronizing a laser beam of the local transceiver with a first block of information signals.

6. The method for distributing a plurality of information signals as in claim 5 wherein the step of transmitting the refractively synchronized laser beam further comprises refractively synchronizing a laser beam of the local transceiver with a second block of transmitted information signals.

7. The method for distributing a plurality of information signals as in claim 6 wherein the step of

refractively synchronizing a laser beam of the local transceiver with a first and second information signals further comprises combining the first and second refraction modulated laser beams.

8. The method for distributing a plurality of information signals as in claim 7 wherein the step of combining the first and second refractively synchronized laser beams further comprises detecting the combined first and second refractively synchronized laser beams.

9. The method for distributing a plurality of information signals as in claim 8 wherein the step of detecting the combined first and second refractively synchronized laser beams further comprises refractively synchronizing a transmission laser with the detected first and second refractively synchronized laser beams.

10. The method for distributing a plurality of information signals as in claim 4 wherein the step of transmitting the refractively synchronized laser beam further comprises refractively synchronizing a laser beam of the local transceiver with a predetermined clock signal assigned to the local transceiver.

11. The method for distributing a plurality of information signals as in claim 4 wherein the step of transmitting the refractively synchronized laser beam further comprises refractively synchronizing a laser beam of the local transceiver with a predetermined clock signal assigned to a first communication group of

the optical communication system which is non-coincident with predetermined clock signals used by other groups.

12. The method for distributing a plurality of information signals as in claim 11 wherein the step of refractively synchronizing a laser beam of the local transceiver with a predetermined clock signal assigned to a first communication group further comprises designating the predetermined clock signal as a master clock and synchronizing a local clock of other transceivers of the first communication group to the master clock.

13. The method for distributing a plurality of information signals as in claim 5 wherein the step of refractively synchronizing the refractively synchronized laser beam further comprises composing an information packet for transmission as a portion of the information signal.

14. The method for distributing a plurality of information signals as in claim 13 wherein the step of composing an information packet further comprises including an identifier of a target of the transmission in a header of the composed transmission.

15. The method for distributing a plurality of information signals as in claim 4 wherein the step of transmitting the refractively synchronized laser beam from the local transceiver, through the waveguide, to another receiver further comprises passing a token

around a ring of the optical communication system to determine a channel availability.

16. The method for distributing a plurality of information signals as in claim 15 wherein the step of passing a token around a ring of the optical communication system further comprises optically removing data from a received laser beam.

17. The method for distributing a plurality of information signals as in claim 16 wherein the step of optically removing data from a received laser beam further comprises detecting a token passed around the ring of the optical communication system in the removed data.

18. The method for distributing a plurality of information signals as in claim 17 wherein the step of optically removing data from a received laser beam further comprises deleting at least some data from the optically removed data and replacing it with other data.

19. The method for distributing a plurality of information signals as in claim 1 wherein the step of transceiving a refractively synchronized laser beam further comprises receiving the refractively synchronized laser beam by the local transceiver from another transceiver.

20. The method for distributing a plurality of information signals as in claim 1 wherein the step of

receiving the refractively synchronized laser beam by the local transceiver from another transceiver further comprises routing the received refractively synchronized laser beam to the receiver of a plurality of receivers of the local transceiver.

21. Apparatus for distributing a plurality of information signals among a plurality of transceivers through an optical communication system, such apparatus comprising:

an optical splitter into an optical waveguide of the optical communication system; and

means for transceiving a refractively synchronized laser beam between the waveguide and a local transceiver, said refractively synchronized laser beam modulated with an information signal of the plurality of information signals and a subcarrier, said subcarrier having a predetermined spectral and amplitude relationship with the information signal.

22. The apparatus for distributing a plurality of information signals as in claim 21 wherein the means for transceiving further comprises means for solving an equation as follows:

$$f_{osample} = \frac{2}{\pi}\{\cos^{-1}(\frac{A}{A_o}) - \{(\frac{A}{A_o})\sqrt{[1.0 - \left(\frac{A}{A_0}\right)^2]]}\}\},$$

where A is modulated amplitude frequency and A_O is clock frequency amplitude.

23. The method for distributing a plurality of information signals as in claim 21 wherein the means for transceiving further comprises means for solving an equation as follows:

$$f_{example} = \frac{2}{\pi}\{\cos^{-1}(\frac{A}{A_o}) - \{(\frac{A}{A_o})\sqrt{[1.0-\left(\frac{A}{A_0}\right)^2]}\}\}\{\frac{2J_1(M)}{M}\{1.0-\left(\frac{A}{A_0}\right)\}\},$$

where A is modulated amplitude frequency, A_0 is clock frequency amplitude, $M = \frac{8\pi\zeta A}{A_0}$, and ζ equals baseband noise amplitude divided by $2A_0$.

24. The apparatus for distributing a plurality of information signals as in claim 21 wherein the means for transceiving the refractively synchronized laser beam further comprises means for transmitting the refractively synchronized laser beam from the local transceiver, through the waveguide, to another receiver.

25. The apparatus for distributing a plurality of information signals as in claim 24 wherein the means for transmitting the refractively synchronized laser beam further comprises means for refractively synchronizing a laser beam of the local transceiver with a first block of information signals.

26. The apparatus for distributing a plurality of information signals as in claim 25 wherein the means for transmitting the refractively synchronized laser

beam further comprises means for refractively synchronizing a laser beam of the local transceiver with a second block of transmitted information signals.

27. The apparatus for distributing a plurality of information signals as in claim 26 wherein the means for refractively synchronizing a laser beam of the local transceiver with a first and second information signals further comprises means for combining the first and second refractively synchronized laser beams.

28. The apparatus for distributing a plurality of information signals as in claim 27 wherein the means for combining the first and second refractively synchronized laser beams further comprises means for detecting the combined first and second refractively synchronized laser beams.

29. The apparatus for distributing a plurality of information signals as in claim 28 wherein the means for detecting the combined first and second refractively synchronized laser beams further comprises means for refractively synchronizing a transmission laser with the detected first and second refractively synchronized laser beams.

30. The apparatus for distributing a plurality of information signals as in claim 24 wherein the means for transmitting the refractively synchronized laser beam further comprises means for refractively synchronizing a laser beam of the local transceiver

with a predetermined clock signal assigned to the local transceiver.

31. The apparatus for distributing a plurality of information signals as in claim 24 wherein the means for transmitting the refractively synchronized laser beam further comprises means for refractively synchronizing a laser beam of the local transceiver with a predetermined clock signal assigned to a first communication group of the optical communication system which is non-coincident with predetermined clock signals used by other groups.

32. The apparatus for distributing a plurality of information signals as in claim 31 wherein the means for refractively synchronizing a laser beam of the local transceiver with a predetermined clock signal assigned to a first communication group further comprises means for designating the predetermined clock signal as a master clock and synchronizing a local clock of other transceivers of the first communication group to the master clock.

33. The apparatus for distributing a plurality of information signals as in claim 25 wherein the means for refractively synchronizing the refractively synchronized laser beam further comprises means for composing an information packet for transmission as a portion of the information signal.

34. The apparatus for distributing a plurality of information signals as in claim 33 wherein the means

for composing an information packet further comprises means for including an identifier of a target of the transmission in a header of the composed transmission.

35. The apparatus for distributing a plurality of information signals as in claim 24 wherein the means for transmitting the refractively synchronized laser beam from the local transceiver, through the waveguide, to another receiver further comprises means for passing a token around a ring of the optical communication system to determine a channel availability.

36. The apparatus for distributing a plurality of information signals as in claim 35 wherein the means for passing a token around a ring of the optical communication system further comprises means for optically removing data from a received laser beam.

37. The apparatus for distributing a plurality of information signals as in claim 36 wherein the means for optically removing data from a received laser beam further comprises means for detecting a token passed around the ring of the optical communication system in the removed data.

38. The apparatus for distributing a plurality of information signals as in claim 37 wherein the means for optically removing data from a received laser beam further comprises means for deleting at least some data from the optically removed data and replacing it with other data.

39. The apparatus for distributing a plurality of information signals as in claim 21 wherein the means for transceiving a refractively synchronized laser beam further comprises means for receiving the refractively synchronized laser beam by the local transceiver from another transceiver.

40. The apparatus for distributing a plurality of information signals as in claim 21 wherein the means for receiving the refractively synchronized laser beam by the local transceiver from another transceiver further comprises means for routing the received refractively synchronized laser beam to the receiver of a plurality of receivers of the local transceiver.

41. Apparatus for distributing a plurality of information signals among a plurality of transceivers through an optical communication system, such apparatus comprising:

an optical splitter into an optical waveguide of the optical communication system; and

a transceiver adapted to transceive a refractively synchronized laser beam between the waveguide and a local transceiver, said refractively synchronized laser beam modulated with an information signal of the plurality of information signals and a subcarrier, said subcarrier having a predetermined spectral and amplitude relationship with the information signal.

42. The apparatus for distributing a plurality of information signals as in claim 41 wherein the transceiver further comprises a transmitter adapted to

transmit the refractively synchronized laser beam from the local transceiver, through the waveguide, to another receiver.

43. The apparatus for distributing a plurality of information signals as in claim 42 wherein the transmitter adapted to transmit the refractively synchronized laser beam further comprises a first optical modulator adapted to refraction modulate a laser beam of the local transceiver with a first block of information signals.

44. The apparatus for distributing a plurality of information signals as in claim 43 wherein the transmitter adapted to transmit the refractively synchronized laser beam further comprises a second optical modulator adapted to refractively synchronize a laser beam of the local transceiver with a second block of transmitted information signals.

45. The apparatus for distributing a plurality of information signals as in claim 44 wherein the first and second optical modulator adapted to refractively synchronize a laser beam of the local transceiver with a first and second block of transmitted information signals further comprises a Cassegrain combiner adapted to combine the first and second refractively synchronized laser beams.

46. The apparatus for distributing a plurality of information signals as in claim 44 wherein the Cassegrain combiner further comprises a photonic

detector adapted to detect the combined first and second refractively synchronized laser beams.

47. The apparatus for distributing a plurality of information signals as in claim 46 wherein the photonic detector further comprises a refractively modulator adapted to refraction modulate a transmission laser with the detected first and second refraction modulated laser beams.

48. The apparatus for distributing a plurality of information signals as in claim 42 wherein the transmitter further comprises a clock refraction modulator adapted to refractively synchronize a laser beam of the local transceiver with a predetermined clock signal assigned to the local transceiver.

49. The apparatus for distributing a plurality of information signals as in claim 42 wherein the transmitter further comprises a first clock adapted to refraction modulate a laser beam of the local transceiver with a predetermined clock signal assigned to a first communication group of the optical communication system which is non-coincident with predetermined clock signals used by other groups.

50. The apparatus for distributing a plurality of information signals as in claim 48 wherein the first clock further comprises a clock detector disposed in at least some of the other transceivers of the plurality of transceivers adapted to recover the predetermined clock signal as a master clock and synchronize a local

clock of the other transceivers of the first communication group to the master clock.

51. The apparatus for distributing a plurality of information signals as in claim 43 wherein the optical modulator further comprises a controller coupled to the optical modulator adapted to compose an information packet for transmission as a portion of the information signal.

52. The apparatus for distributing a plurality of information signals as in claim 41 wherein the further comprises a receiver adapted to receive the refraction modulated laser beam by the local transceiver from another transceiver.

53. The apparatus for distributing a plurality of information signals as in claim 41 wherein the transceiver further comprises a router & switch adapted to route the received refraction modulated laser beam to the receiver of a plurality of receivers of the local transceiver.

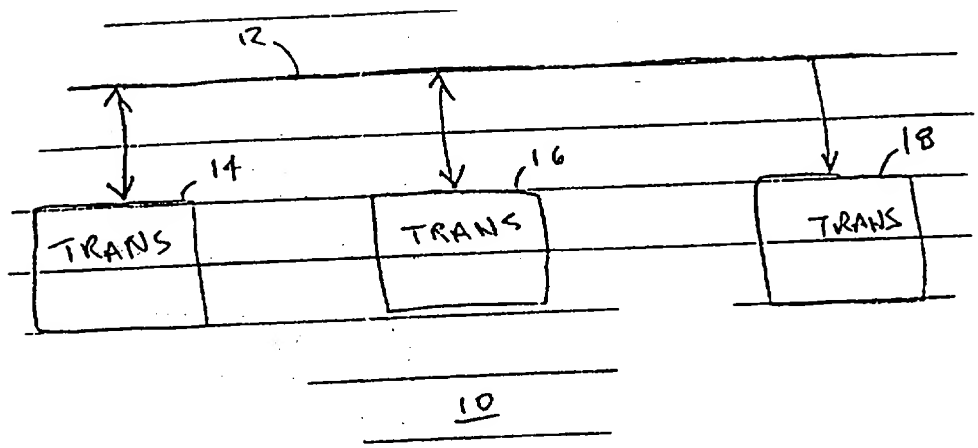


FIG. 1

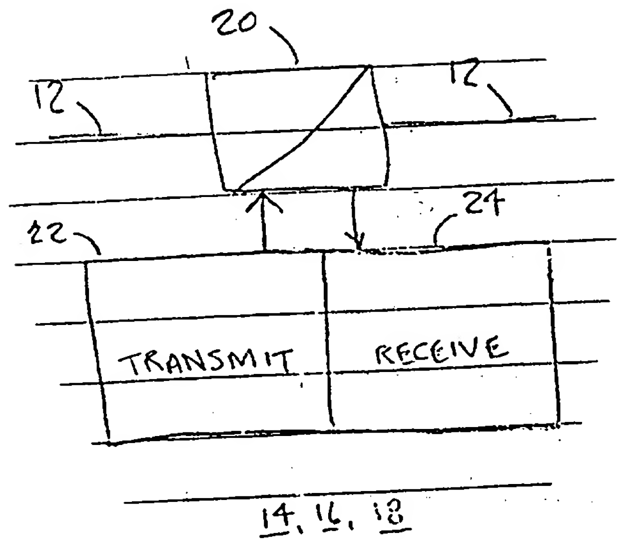


FIG. 2

Figure 3 – User Add/Drop Capability

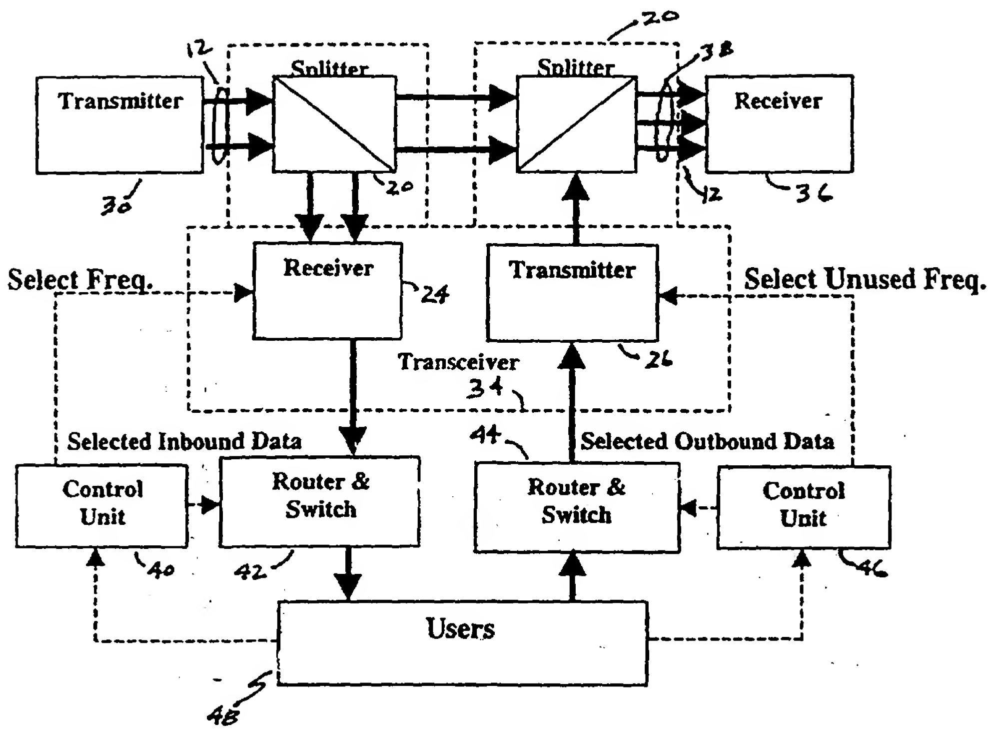


FIG. 3

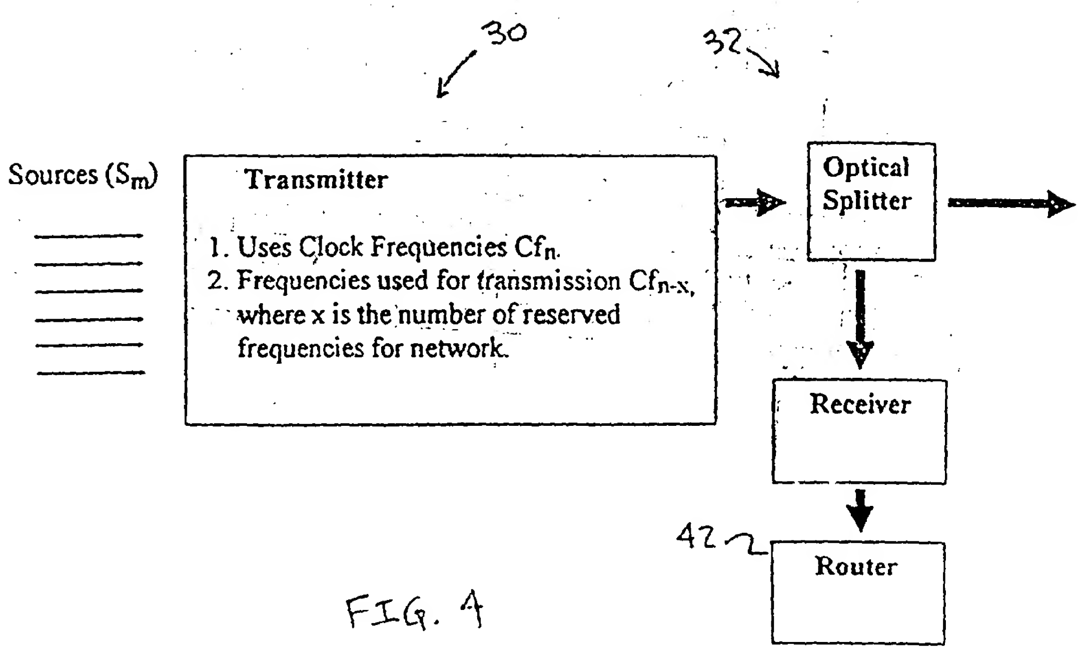

30
32
Sources (S_m)
Transmitter
1. Uses Clock Frequencies Cf_n.
2. Frequencies used for transmission Cf_{n-x}, where x is the number of reserved frequencies for network.
Optical Splitter
Receiver
42
Router

FIG. 4

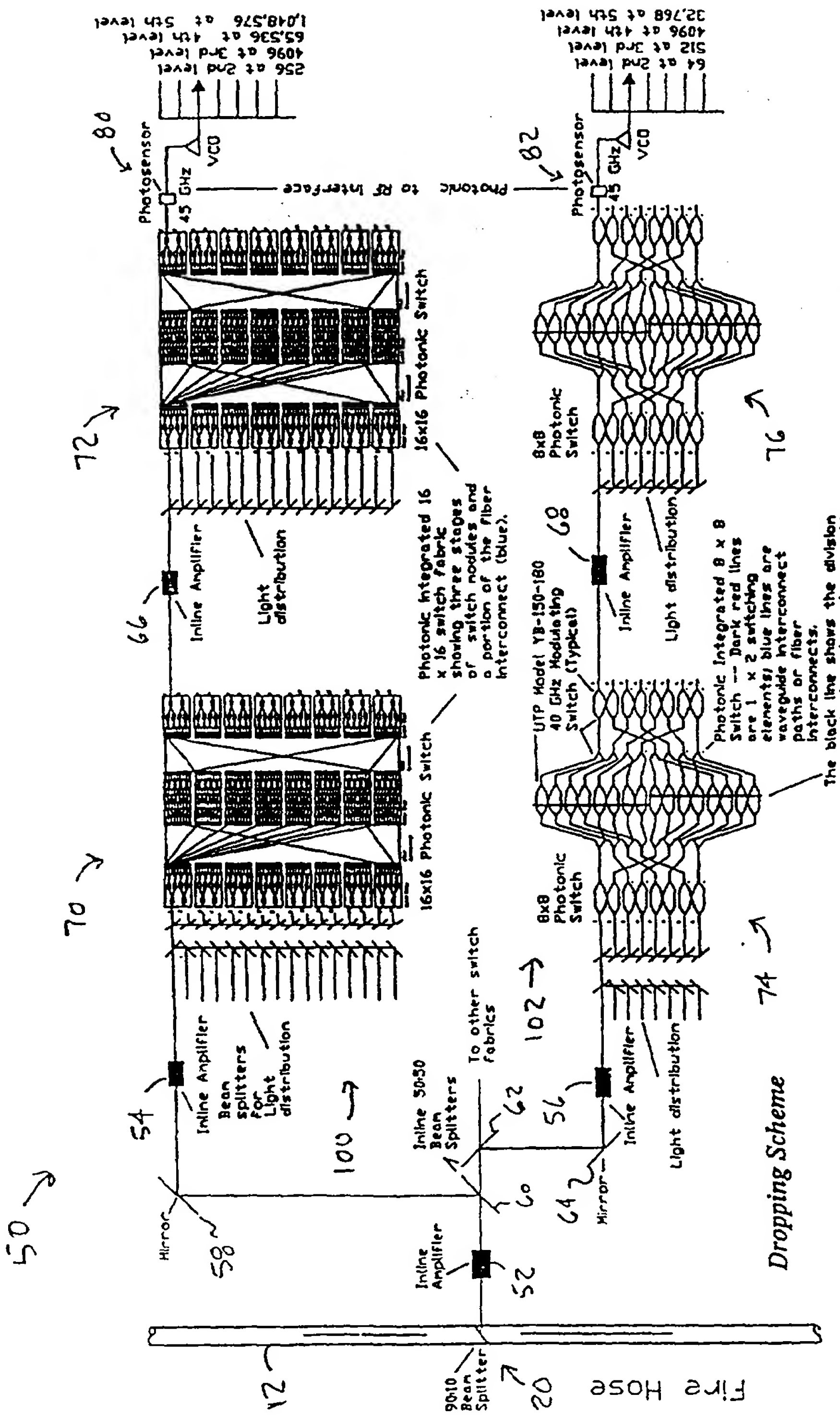

Fire Hose
90:10 Beam Splitter
Inline Amplifier
Mirror
Inline 50:50 Beam Splitters
To other switch fabrics
Inline Amplifier
Beam splitters for Light distribution
16x16 Photonic Switch
Photonic Integrated 16 x 16 switch fabric showing three stages of switch modules and a portion of the fiber interconnect (blue).
Inline Amplifier
Light distribution
Photosensor
45 GHz
VCO
Photonic to RF Interface
256 at 2nd level
4096 at 3rd level
65,536 at 4th level
1,048,576 at 5th level
Light distribution
8x8 Photonic Switch
UTP Model YB-150-180 40 GHz Modulating Switch (Typical)
Photonic Integrated 8 x 8 Switch -- Dark red lines are 1 x 2 switching elements; blue lines are waveguide interconnect paths or fiber interconnects.
The black line shows the division of switch elements and waveguides on each of the two identical substrates.
64 at 2nd level
512 at 3rd level
4096 at 4th level
32,768 at 5th level
Dropping Scheme
50
12
20
52
58
60
62
64
54
56
100
102
70
72
74
76
66
68
80
82

FIG. 5

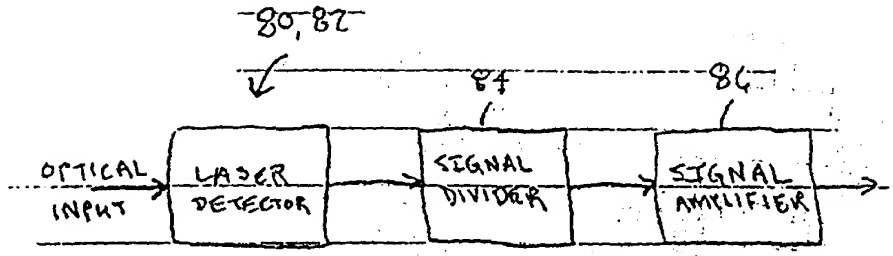

80, 82
84
86
OPTICAL INPUT
LASER DETECTOR
SIGNAL DIVIDER
SIGNAL AMPLIFIER

FIG. 6

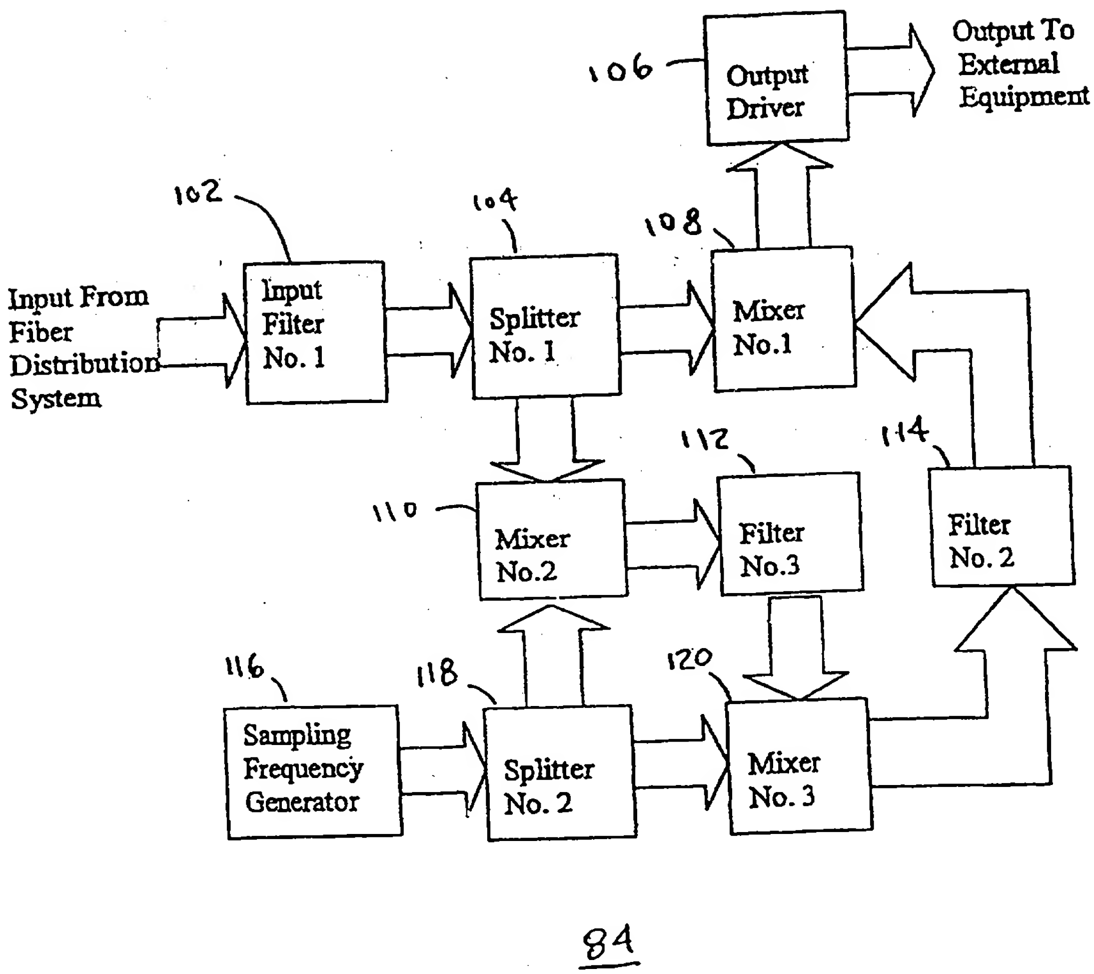

Output Driver
106
Output To External Equipment
102
104
108
Input From Fiber Distribution System
Input Filter No. 1
Splitter No. 1
Mixer No.1
112
114
110
Mixer No.2
Filter No.3
Filter No. 2
116
118
120
Sampling Frequency Generator
Splitter No. 2
Mixer No. 3
84

FIG. 7

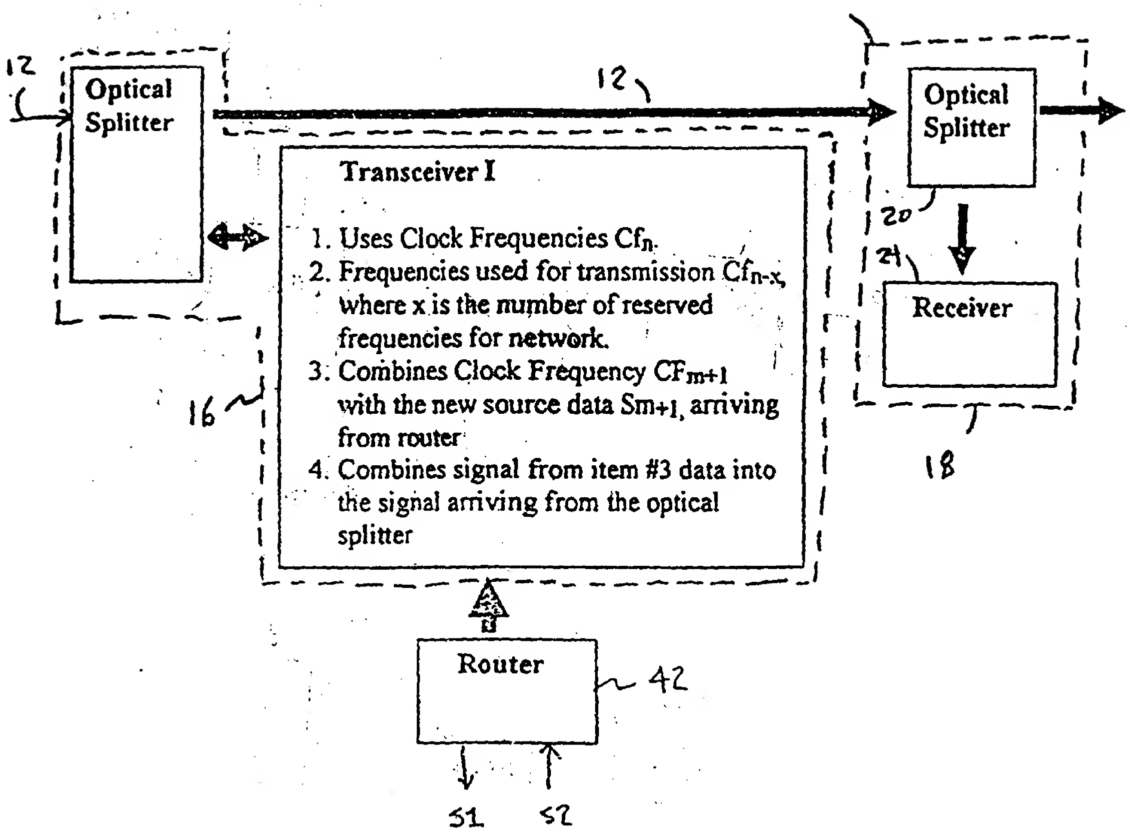

12
Optical Splitter
12
Optical Splitter
Transceiver I
1. Uses Clock Frequencies Cf_n.
2. Frequencies used for transmission Cf_{n-x}, where x is the number of reserved frequencies for network.
3. Combines Clock Frequency CF_{m+1} with the new source data Sm_{+1}, arriving from router
4. Combines signal from item #3 data into the signal arriving from the optical splitter
20
24
Receiver
16
18
Router
42
51
52

FIG. 8

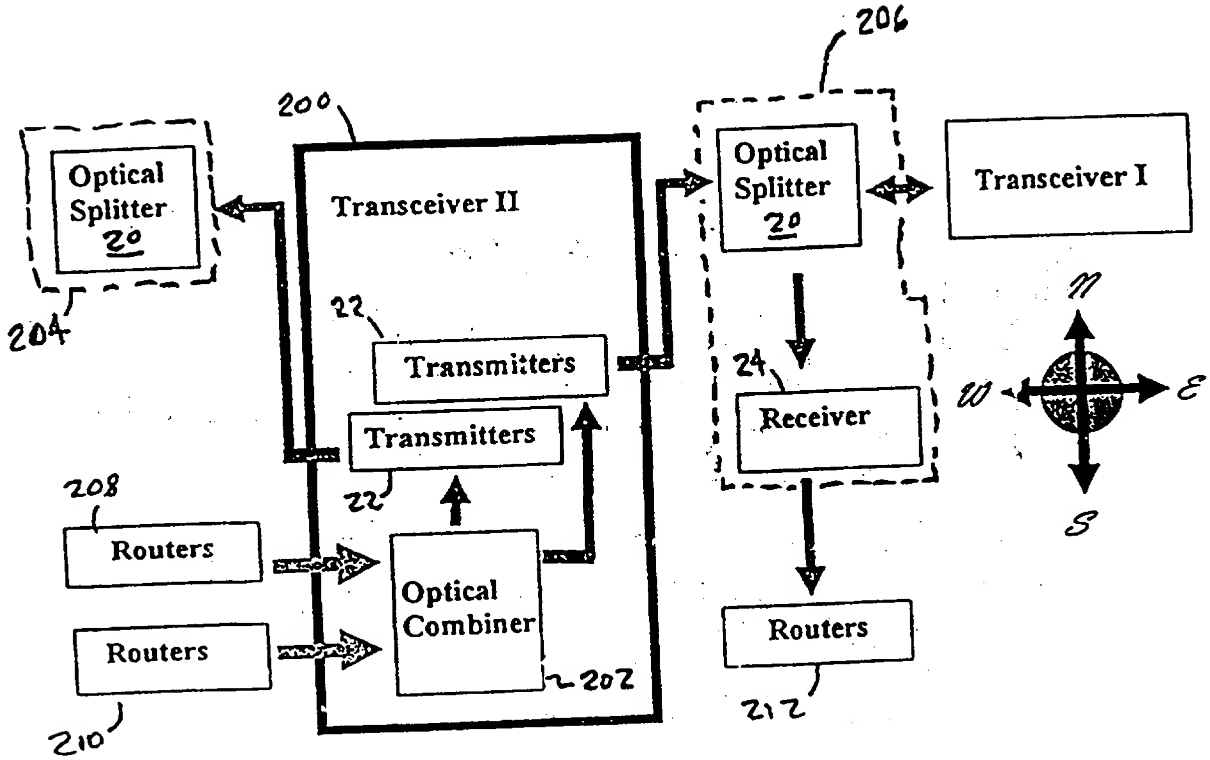
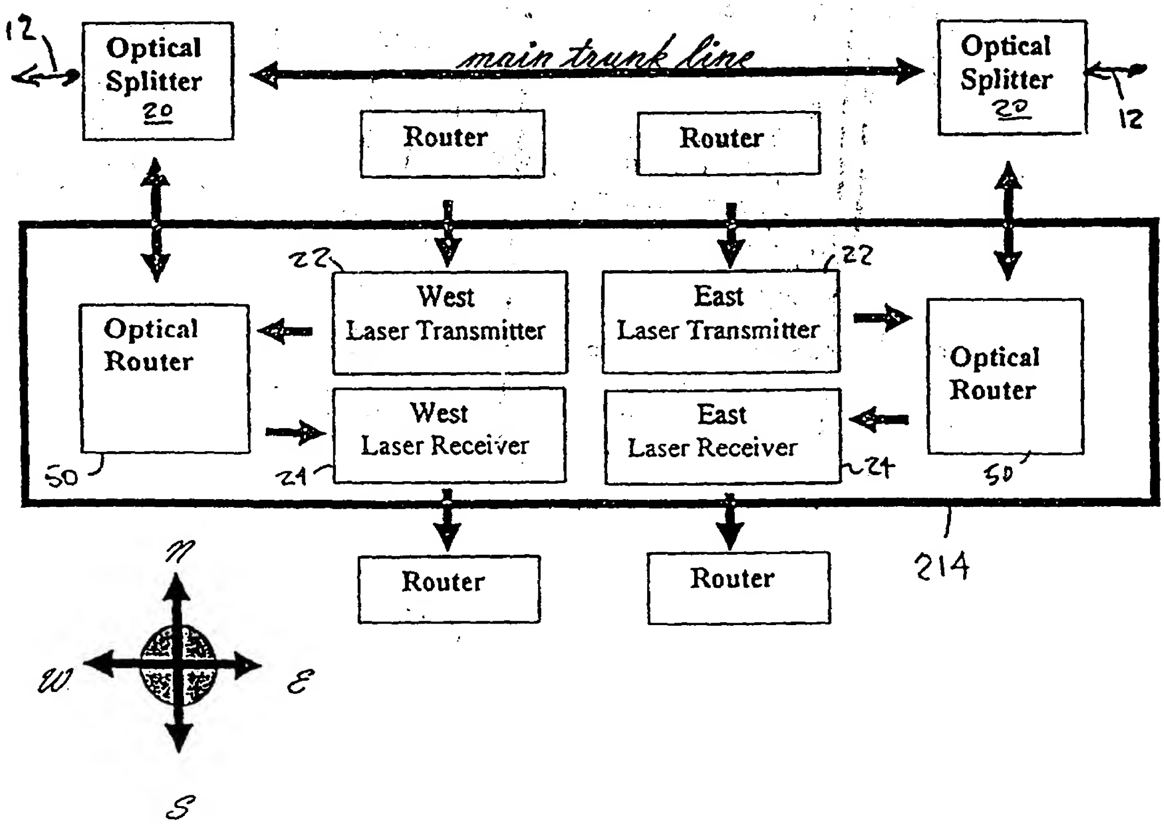
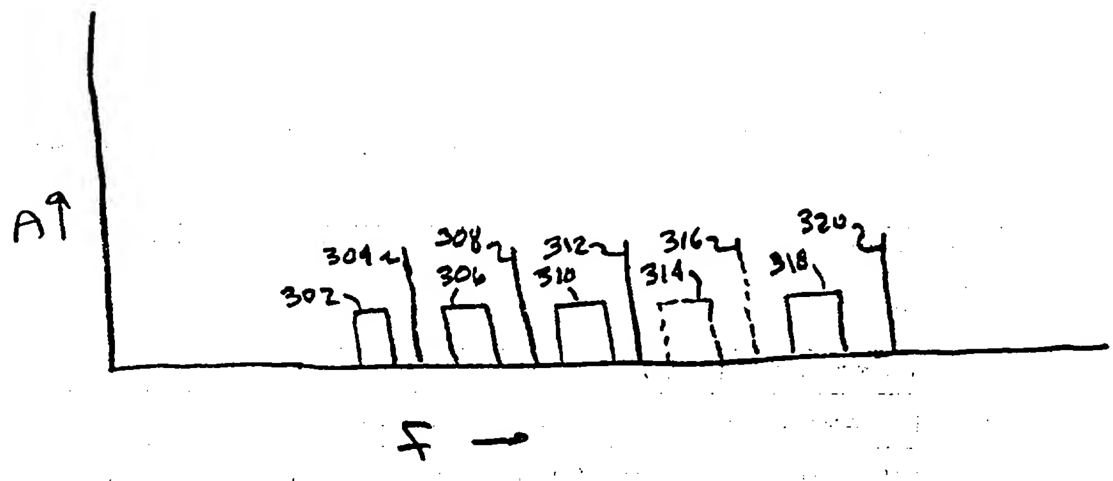

Optical
Splitter
20
204
200
Transceiver II
22
Transmitters
Transmitters
22
208
Routers
Routers
210
Optical
Combiner
202
206
Optical
Splitter
20
Transceiver I
24
Receiver
Routers
212
N
W
E
S

FIG. 9



12
Optical Splitter 20
main trunk line
Optical Splitter 20
12
Router
Router
22
22
West Laser Transmitter
East Laser Transmitter
Optical Router
Optical Router
West Laser Receiver
East Laser Receiver
50
24
24
50
214
Router
Router
N
W
E
S

FIG. 10



300

FIG. 11

INTERNATIONAL SEARCH REPORT	International application No. PCT/US00/07328

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :H04B 10/00
US CL :359/152
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/152, 158, 165, 174, 177, 179

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST
searched terms: refractively synchronized, subcarrier multiplex

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,440,418 A (ISHIMURA et al) 08 August 1995, col. 1, lines 61-68, col. 2, lines 1-68.	1,4,15-21,24,35-43,51-53
--- Y		------------5- 9,13,14, 25-29,33, 34,44,45
Y	US 5,561,551 A (IWASAKI et al) 01 October 1996, col. 2, lines 51-68, col. 2, lines 1-51.	5-9,13, 14,25-29, 33,34,44, 45

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 MAY 2000	28 JUL 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	DALZID SINGH
Facsimile No. (703) 305-3230	Telephone No. (703) 305-3900